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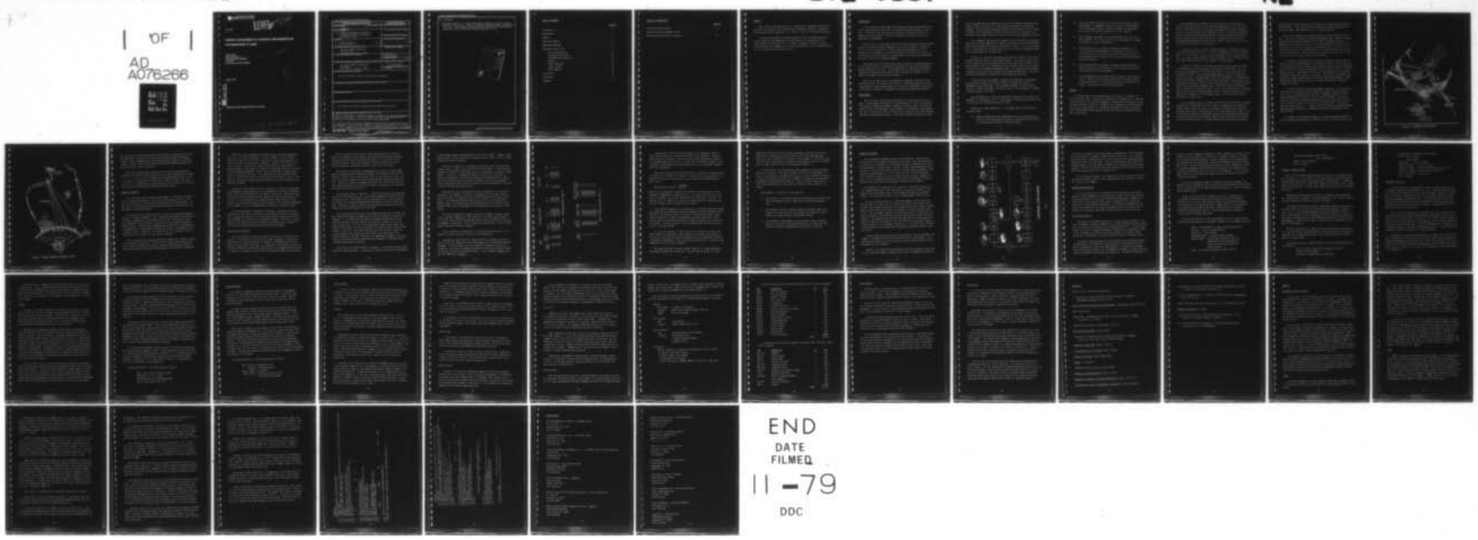

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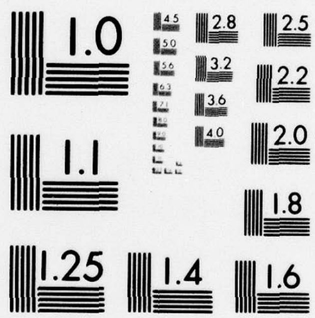


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# CONCEPT DEVELOPMENT OF AUTOMATIC INSTRUMENTATION FOR MONITORING OF DAMS

movements

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28 May 1979



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A study was undertaken to determine a method or methods for monitoring movements of large concrete dams. A fully automated instrument system based on this method was to be designed for use in dam failure monitoring.

A literature search for possible methods and comparision of capabilities including atmospheric refraction error modeling of optical systems lead to the selection of laser ranging as the best method for measuring dam deflection. The system


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developed consists of a laser range meter pointed at an array of retroflectors on the dam by a computer controlled azimuth-elevation instrumentation mount. The computer also handles data collection and correction and reports to a remote terminal at the dam operator's site.

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# PREFACE

This work was authorized by the U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, under OCE Work Unit 010303/31161 entitled, "Continuous Monitoring System for Dam Safety". The COTR for this work was Kenneth Robertson.

A study was performed to determine methods suitable for monitoring large concrete dams for any movements which might indicate an inpending failure. Laser ranging is compared to other techniques, atmospheric refraction effects are modeled and the equipment and specifications necessary for the implementation of such a monitoring system are discussed.

## INTRODUCTION

A 1972 study done by the Army Corp of Engineers identified 20,000 dams in the U.S. whose failure would result in significant property damage or loss of life. With construction starting on an average of 100 dams per month this number is bound to increase. The costs involved in the failure of one of these dams is tremendous.

Statistically, a catastrophic dam failure causes between $1500 and $178000 worth of residential property damage per acre-foot of reservoir, along with 0.4 to 45 deaths per acre-foot in cases where the downstream area is not evacuated. As an example of a recent dam failure, the June 1976 collapse of the Teton Dam in Idaho resulted in eleven deaths and caused an estimated $400 million to $1 billion in property damages.

This potential for destruction has created interest in the development of an instrument capable of automatically monitoring a large dam and providing advance warning of a failure. Given enough time, the dam structure could be repaired and stabilized, the water level of the reservoir lowered, or the people and property below the dam evacuated.

With this in mind, the U.S. Army Engineer Topographic Laboratories has funded this study, the objective of which is to investigate methods of detecting movement in large concrete dams and to develop an instrument system using off-the-shelf technology to implement the method or methods found suitable.

## REQUIREMENTS

One of the most easily detected indication of a pending dam failure is a physical displacement of some part of the dam structure. Since all dams move in response to temperature changes, changes in reservoir water level and the effects of water table heights on the abutments and foundation, displacements will have to be measured over a period of time to separate this normal movement from that associated with failure. A dam failure usually involves a sliding

of the dam along the rock foundation, parts of the foundation slipping along seams or faults in the rock, or a part of the dam structure cracking and slipping. Concrete gravity dams which depend on their weight to stay in place are particularly susceptible to these failures and also to toppling if the resultant of the weight and water forces lies outside the footprint of the dam.

In an embankment dam, excessive seepage, an early indication of problems, would not be detected immediately. Rather, the seepage would be detected only after having undermined a portion of the dam and caused it to slip or collapse. Thus, a measurement of this type would not be as suitable for embankment dams as for gravity dams but could be used.

A failure of a concrete arch dam occurring in the structure itself would probably take the form of a catastrophic rupture. This type of failure would best be predicted by monitoring the stress levels inside the structure, but it might mainfest itself as a deformation of the external surface and be subject to prediction by a movement measurement device. Arch dams also fail through slippage or cracking of their abutment and foundation structures. This would be easily detectable as a deflection in the downstream direction.

A motion detection instrument, although most applicable to monitoring gravity types of dams, could also be useful in insuring the safety of embankment and archtype dams. If any abnormal movement of a dam could be detected, it might anticipate a failure in time to allow preventive or damage reducing measures to be taken.

The requirements for a monitor system which would be able to detect this movement were developed by the U.S. Army Engineer Topographic Laboratories and are given in the following description of work:

Develop one or more concepts for an instrument which will perform the following tasks:

- Measure automatically the displacement of up to fifty points on a structure, such displacements being in one given direction relative to a given point which may be considered stable.

- Record and compare the results with original positions to detect displacements. A permanent record will be kept of displacements. If any displacement exceeds a specified amount, the instrument shall notify the operator responsible for the structure.

- The instrument shall make a set of measurements twice per day or when commanded. The average time for the measurement of a single point shall not exceed five minutes.

- The instrument shall be capable of making measurements with a relative accuracy (measurements of displacements relative to an initial position are required rather than absolute position) of 10 millimeters from a position that may be from 100 to 3000 meters from the structure.

- The instrument shall be capable of making measurements under all weather conditions in which details of the structure are visible from the position of the instrument.

- The instrumentation may include suitable targets on the structure itself. Points on the structure may be as close as three meters from adjacent points. The structure may be up to 1500 meters in length. Targets may be at different elevations.

## METHODS

At present there are several methods used to monitor the behavior of concrete gravity dams. During their construction, instrumentation is imbedded in the structure. This allows measurement of temperatures and stresses in the concrete and joints of the dam. Plumbbobs and clinometers in the dam measure any tilting of the structure. Piezometers and compression meters installed under the dam detect water seepage and show the interaction between the dam and its foundation.

This instrumentation, however, cannot be installed in dams whose construction has been completed. The older dams among these are the ones most likely to need monitoring, and this may be accomplished by another method in wide use. By establishing stable observation piers in a pattern downstream of the dam, precision surveying techniques may be used to measure the displacements of targets placed on the dam surface. Using many observations and triangulating between observation piers and targets, the position of a target may be determined within a few millimeters.

A survey of this sort is time consuming, however, and expensive because of the experienced crew needed to set up the instruments and take the measurements. Also, the remote location of many dams makes frequent surveys unfeasible. In light of these problems and the requirement for an automated monitoring system, manual surveying is not deemed a suitable method.

A review of literature on movement and deformation measurement produced four methods which could be adapted to monitoring concrete dams. The first, precision photogrammetry, has already been tested for use in measuring the deformation of dams. In this method photographs are taken of the dam from several positions. The photographic plates are then measured to determine the positions of targets mounted on the dam face with respect to the camera piers. Subsequent plates may be taken and any target deflections calculated by comparison with the original photographic data. This process has many problems which eliminated it from further study. First is the delay involved in development of the plates and the measurement process. Second, the method would be impossible to automate. Like the manual survey, it also involves skilled personnel and remote sites.

Laser holography and interferometry have been used successfully to measure deformations of small bodies at close range. By comparing two holographs of objects taken at different times it is possible to determine how a body has deformed under stress. Deformations have also been measured by changes in the fringe patterns captured in holographs using laser interferometry techniques. It could be possible to extend these methods to measure deflections of larger structures from a distance. Although theoretically interesting, holography

and diffraction fringe analysis did not appear to be immediately applicable to dam monitoring. Since this study is mainly concerned with applying off-the-shelf technology, these methods were not considered further.

The last two methods involve applications of present surveying techniques. The first, collimation, measures the apparent angle between a reference receiver and the target receiver as seen from the instrument position. A deflection of the target receiver in a direction perpendicular to the line of sight would be detected as a change in the measured angle. The second method involves the use of a laser distance meter to accurately measure the distance to a reflecting target. Any deflection of the target along the line of sight would be shown as a change in the measured distance.

In a monitoring system based on collimation (Figure 1), there would be a laser collimator on one abutment of the dam and a series of active targets on the dam structure, while reference targets would be placed on the far abutment. The collimator would sweep a laser beam across the target array at a constant angular velocity. Each target would react to the appearance of the beam on its aperture and send a pulse to a processor. The timing of the pulses from the various targets would be used to calculate angular displacements. These displacements would be monitored for any change which might be caused by slippage of the dam.

In a system employing distance measurement (Figure 2), a laser distance meter would be located at a point along the periphery of the lake having a clear view of the upstream face of the dam. Placement allowing a line of sight perpendicular to the axis of the dam would be optimal. An array of passive retroreflectors would be mounted along the dam and reference targets would be placed on either side of the dam on stable ground. The distance meter would be pointed at the targets one at a time and the distances measured. Monitoring these distances for changes would show any displacement of the dam over time.

An automatic collimating instrument is already being manufactured by an Italian company, Officine Galileo, and sold in the U.S. by Terra Metrics, Inc.

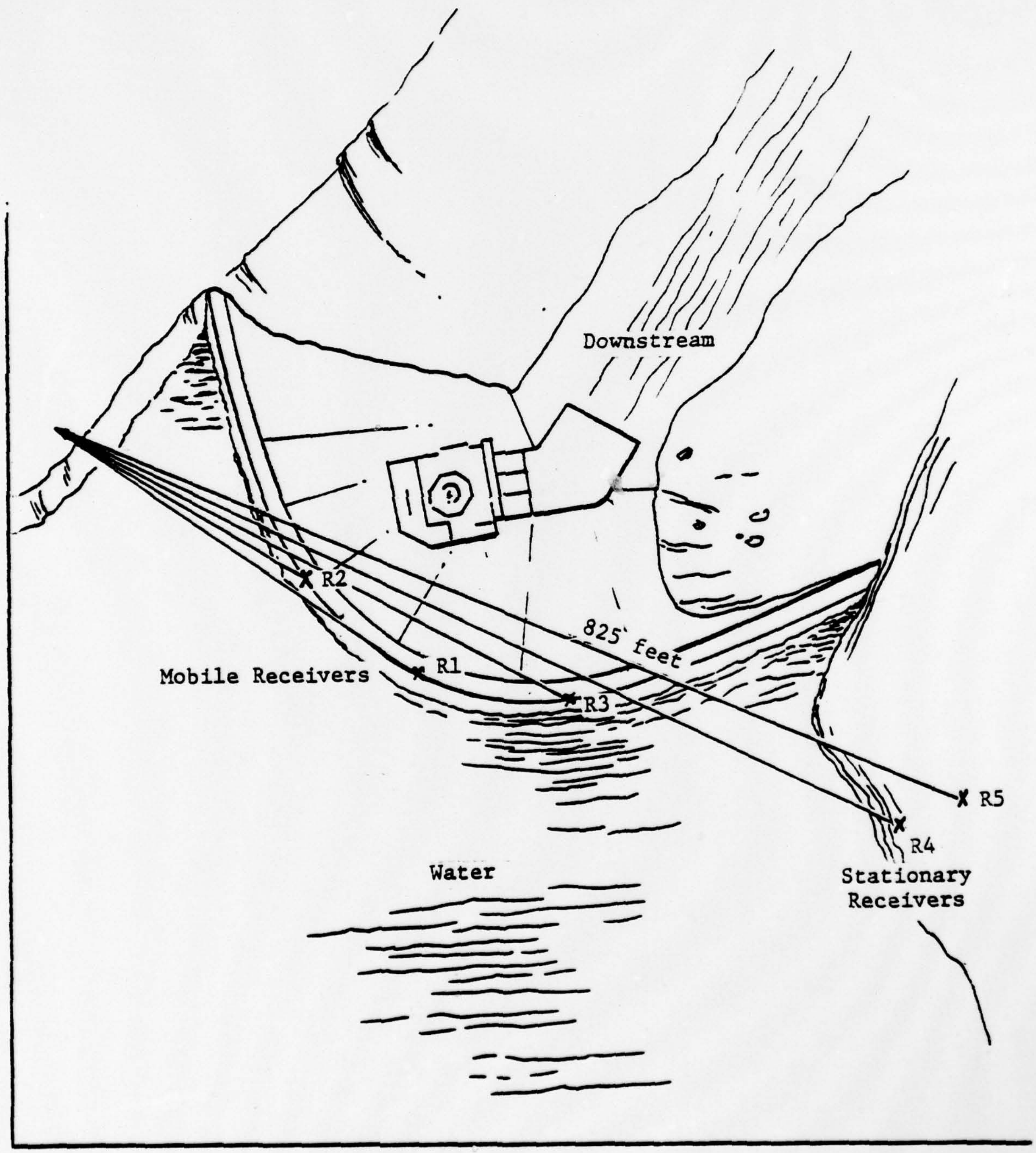



Figure 1 Collimation System Layout

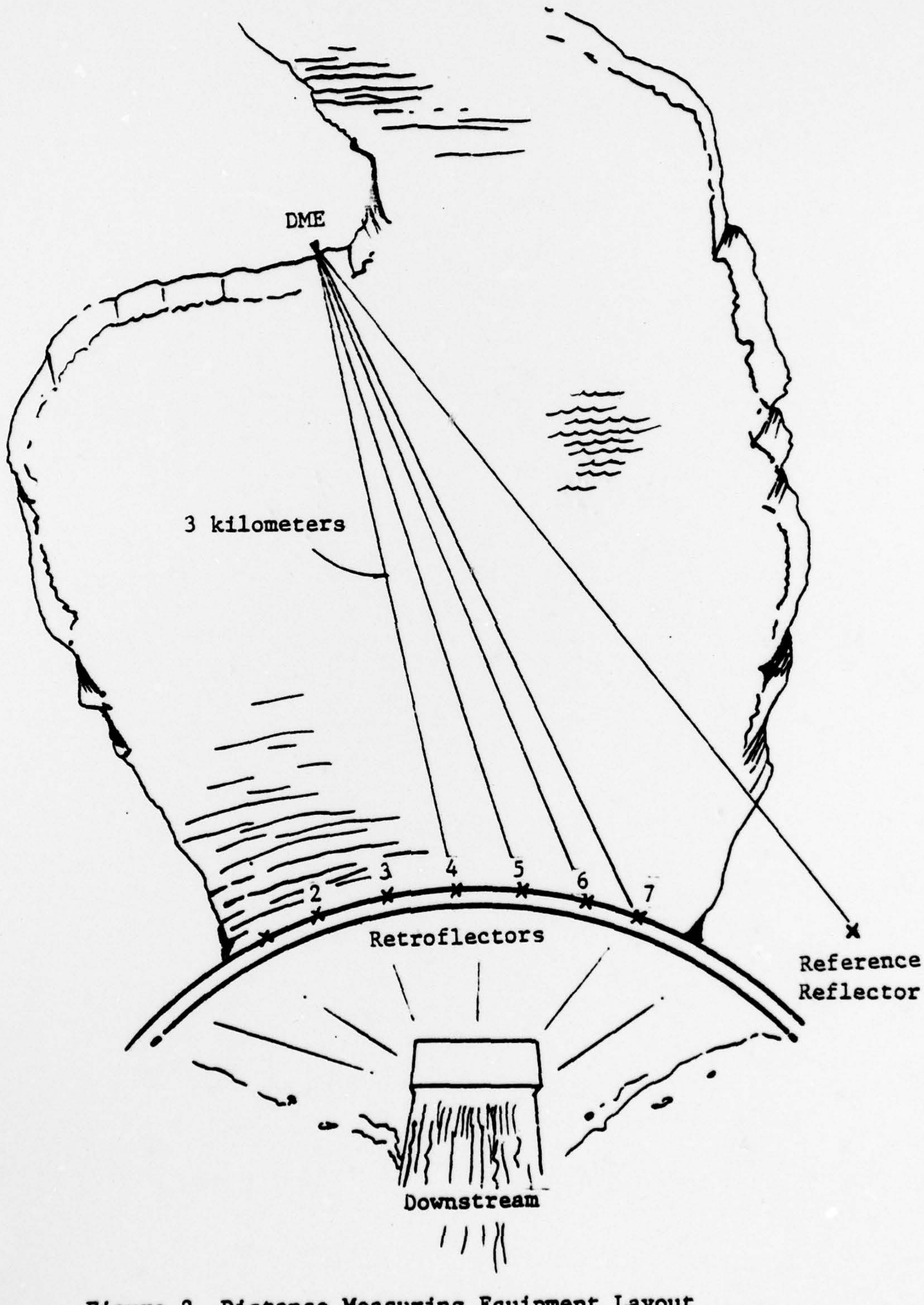



Figure 2 Distance Measuring Equipment Layout

This system is presently being tested by the Bureau of Reclamation for use in dam monitoring. No system is available incorporating distance measuring. However, several companies make laser distance meters capable of reacting to computer control. These include the Hewlett Packard HP3808-A and the Terrameter LDM2 made by Terra Technology.

Since both of these methods may be placed in service using available equipment and each may be used automatically, further investigation was undertaken. The accuracy of the instruments involved seemed sufficient to allow a displacement of 1 centimeter to be detected. However, the fact that both systems use the transmission of light indicated that the effects of refraction on collimation and distance measurements should be modeled.

## REFRACTION EFFECTS

As a light wave travels through the atmosphere, it encounters regions of air of varying characteristics. Its overall path becomes curved as it is bent, or refracted, at the interfaces between any two of these regions. The net result is that the observed distance and direction to an object are not the same as the measured values.

The variations in the characteristics of the air are usually modeled in terms of a standard atmosphere. This is based on knowledge of the variations of density, temperature, and pressure with altitude. The manner in which other parameters, such as index of refraction, vary may then be defined in terms of these. Various other assumptions may be made for the development of a standard model. Some geometric base must be selected, for example, a flat or spherical earth. Typically, only the mixture of dry atmospheric gases is considered and the presence of water vapor is ignored.

This is sufficient for applications which require only a general estimate of the effects of refraction. In the case of a dam monitoring system, however, diurnal and seasonal variations in weather conditions and features in local terrain may also contribute significantly to the effects of refraction.

While the standard atmosphere is modeled using an average temperature lapse rate, the actual temperature of the air depends on current weather conditions as well as on altitude. The level of water vapor present also varies, not only with the specific climate at a station, but with the local terrain as well. The case of a station associated with a dam provides a striking example of the effects of changes in ground characteristics on those of the overlaying atmosphere. The air over the land mass is significantly less moist than that over water. The temperature of the atmospheric gases tends to stratify with respect to the actual surfaces present, so that in the area near the dam face conditions depart markedly from those assumed for the standard atmosphere.

Estimation of the amount by which a light ray is refracted is dependent upon knowledge of some measurement of the atmosphere's refractive properties, such as the refractive modulus or the index of refraction. These may be computed based on the measured pressure, temperature, and relative humidity at a station. It is also possible to estimate them for points which are close enough to the station that either the characteristics of a standard atmosphere may be assumed or the local meteorological conditions accurately modeled.

With such knowledge of atmospheric conditions, it becomes possible to compensate for the effects of refraction on a measured distance or displacement. Computation of the refraction correction may be performed by ray tracing techniques, or through use of an empirical formula. The choice of method depends on the degree of accuracy required by the application. Details of the refraction modeling program are contained in the Appendix.

## Application of the Model

Two sets of typical transmitter/target locations were selected for this analysis. A ray-trace was run for the set shown in Figure 1 using the segmented model to include the effects of changes in temperature and relative humidity in the region of the dam. The differences in the amount of refraction correction obtained for different aspect angles of the segmented model provide an estimate of the amount of error which a collimation system would encounter.

The face of the dam was chosen as the reference surface in order to depict the atmospheric stratification associated with its vertical surface. Vertical refraction was not treated by the model, as it does not affect a collimation system. While other sources of lateral refraction do exist, they are anomalous; this model, therefore, depicts the "best case".

The curvature of the dam was approximated by a series of three tangent planes defining successive reference systems. Each segment of the model was defined in terms of one of these planes with its own coordinate system. The data from adjacent segments were then related through coordinate transformation. Conditions within each segment were defined in terms of the nature of the terrain over which the ray must pass--water or non-water, with both land and concrete treated as the latter.

Three general areas are involved: a water region between the transmitter and the dam, the dam itself, and a water region between the dam and the stationary receivers. The primary source of horizontal error in this layout is the variation in conditions through which the different lines of sight must pass. The lines to mobile receivers pass through one water and one non-water region while the third passes over water only.

The horizontal refraction error was computed for each line of sight, and the differences between the computed errors for the different receivers were examined. It was found that the angular discrepancy between the true and observed positions varied too much to be treated as a simple bias for the entire target array. The error associated with a single target ranged from 0.006 to 0.439 feet for an array which had its closest target at 235 feet and farthest at 800 feet. The largest relative error for adjacent targets was 0.03475 degrees or 618 parts per million (PPM), while the smallest was 0.000071 degrees or one PPM. These data are summarized in Table 1, along with the errors associated with distance measuring equipment for the same targets and some meteorological conditions.

This layout was selected because, in general, a collimation system is most useful over short distances. It obtains its greatest accuracy for measurements

of displacement which are perpendicular to its line of sight. Together, these characteristics require that such a system be placed so that its line of sight parallels the face of the dam.

In practice, however, it is extremely difficult to know the temperature along the line of sight to the accuracy used in this model. It would require placement of sensors at each target, which is not possible in a passive target system. In addition, a mathematical model would have to be developed to depict the atmospheric stratification between the instrument and its targets. Each dam site would require individual treatment and the model parameters could be determined with sufficient accuracy only through analysis of the data collected from the operational system.

Unfortunately, this configuration is quite vulnerable to conditions of refraction. For example, a variation in temperature of one degree Celsius typically results in a change of the refractive modulus on the order of one N-unit. The resultant additional angular error for a line of sight which makes an angle of 85 degrees with the gradient would be over two and a half seconds (2.556), which corresponds to 12 millimeters over a distance of 1000 meters.

The refractive modulus is highly sensitive to changes in weather conditions, especially temperature. The variation in the water vapor content of the air over water and over nearby land masses yields a significant variation in atmospheric temperature. This is especially pronounced in a region of high temperatures and low relative humidity.

It was, therefore, concluded that a collimation system could not be expected to provide sufficient accuracy for this application.

Although this target layout is appropriate for a collimation system, it does not take full advantage of the range capabilities of distance measuring equipment. A second target array was, therefore, examined, in which the transmitter was located 3 kilometers upstream of the dam, more than ten times the distance involved in the previous layout. This is shown in Figure 2 and the data summarized in Table 2.

| ARRAY | | COLLIMATION SYSTEM | | | | DME SYSTEM | |
|---|---|---|---|---|---|---|---|
| Target Number | Total Distance Feet | Degrees | Mils | Feet | PPM | Feet | PPM |
| R1 | 355 | +0.001802 | +0.03204 | 0.011 | 32 | 0.0003 | 1 |
| R2 | 235 | +0.001513 | +0.02690 | 0.006 | 27 | 0.0003 | 1 |
| R3 | 470 | +0.001442 | +0.02563 | 0.012 | 26 | 0.0039 | 8 |
| R4 | 755 | -0.3304 | -0.59207 | 0.439 | 592 | 0.0004 | 1 |
| R5 | 800 | -0.016471 | -0.29282 | 0.230 | 293 | 0.0006 | 1 |

TABLE 1 REFRACTION ERROR, ARRAY #1

| Target Number | Total Distance Meters | Total Error Meters | Total Error PPM | Error with Respect To Reference Target Meters | Error with Respect To Reference Target PPM |
|---|---|---|---|---|---|
| 1 | 3076 | 0.0228 | 7 | 0.0006 | <<1 |
| 2 | 3066 | 0.0227 | 7 | 0.0005 | <<1 |
| 3 | 3039 | 0.0225 | 7 | 0.0003 | <<1 |
| 4 | 3000 | 0.0222 | 7 | 0.0000 | <<1 |
| 5 | 3039 | 0.0225 | 7 | 0.0003 | <<1 |
| 6 | 3066 | 0.0227 | 7 | 0.0005 | <<1 |
| 7 | 3076 | 0.0228 | 7 | 0.0006 | <<1 |
| R | 3100 | 0.0222 | 7 | ------ | <<1 |

TABLE 2 REFRACTION ERROR, ARRAY # 2

A temperature of 30° Celsius was assumed at the transmitter, while a lower value was used over the water where the air was saturated. Under the conditions used in analysis of the first array, these temperatures translate to a maximum index of refraction of 1.000350 and a minimum of 1.000334. Over a distance of 3000 meters, the range refraction error is, therefore, approximately two centimeters.

Unlike the refraction error associated with a collimation system, however, the range error is subject to reduction. One approach is the application of a standard refraction correction, such as that used by the HP3808-A Distance Meter. Here,

$$\text{PPM Correction} = 279.42 - \frac{105.885\ P}{273.2 + T}$$

where P is the atmospheric pressure in millimeters of mercury and T is the atmospheric temperature in degrees Celsius. For this target array, T is 30° and P is 760 mmHg. Use of this formula yields a range error of 14 PPM. The residual error is caused by the variation in meteorological conditions along the line of sight, which is ignored by the formula.

A more effective approach is to make use of a stationary reference target and assume that any difference between its apparent and true distance from the DME may be attributable solely to refraction. Measured distances to other targets have lines of sight of approximately the same length which travel through regions of similar meteorological conditions may then be corrected by this amount. As shown in Table 2, this procedure reduces the error for this array to less than one PPM.

The refractive modulus is highly sensitive to changes in weather conditions, especially temperature. The variation in the water vapor content of the air over water and over nearly land masses yields a significant variation in atmospheric temperature. This is especially pronounced in a region of high temperatures and low relative humidity.

The range error may be further reduced, however, by taking advantage of the geometric properties of the array. For this type of layout, all lines

sight pass through essentially the same atmospheric conditions so that the range errors, expressed in parts per million, are of the same magnitude. These errors may, therefore, be treated as a bias common to all lines of sight and effectively eliminated by a technique of analyzing the ratios of adjacent lines of sight instead of the directly measured distances.

In certain cases, the additional accuracy inherent in a dual wavelength device will be needed. With this equipment, the relative displacement of light of two different wavelengths may be used to directly measure the amount of refraction between the target and transmitter, bypassing the requirement of measurement of meteorological parameters. This will handle those cases in which the range refraction error cannot be treated as a bias common to all targets.

Some examples of conditions of this type are:

1) The presence of land masses between the transmitter and targets such that the different lines of sight pass over different amounts of land.

2) The presence of objects, whether natural or man-made, which cast shadows across the array in such a manner that different lines of sight pass through different light/shadow patterns.

3) The presence of topographical variations which subject different parts of the array to consistently different wind conditions and, therefore, different temperatures and refractive conditions.

## OPERATION ALGORITHM

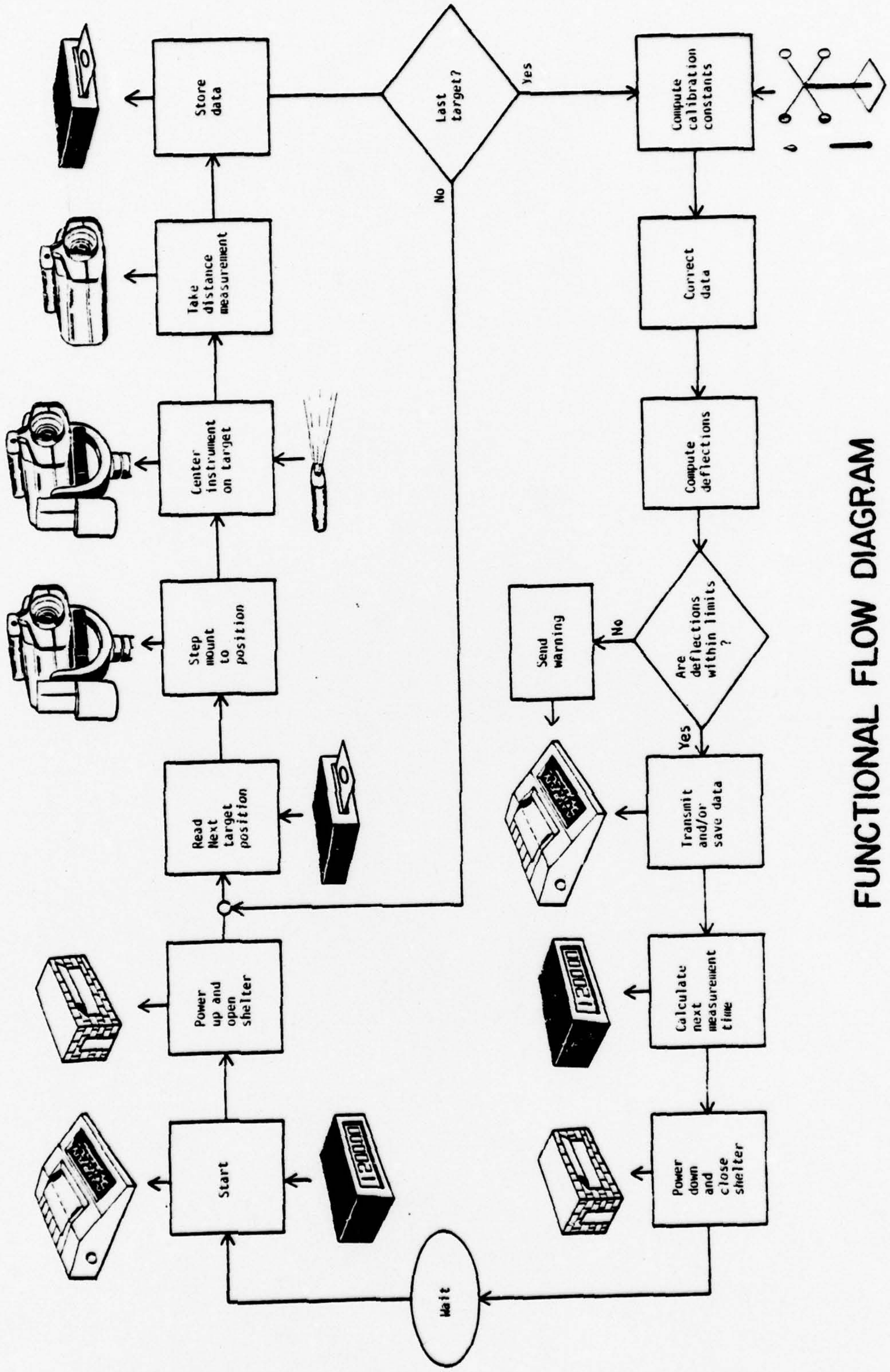
Once the method of movement detection was determined, a more detailed description of the instuments functions was developed. This algorithm served to finalize the configuration of the system and help in specifying the individual components. As stated above, the basic distance measuring monitor would consist of a laser distance meter located at a point along the perphery of the reservoir from whch there is a clear view of the dam. Reflecting targets would be mounted along the top and on either side of the dam. Figure 3 consists of a block diagram showing the control functions necessary to operate the monitoring system and the peripherals addressed by the computer.

The computer will spend most of its time in an idle mode waiting for a start command from either a real time clock or the off-site terminal. The computer would then supply power to the equipment and open the instrument shelter. It would then be ready to start the measurement taking process.

The first operation would be to take measurements of the calibration targets mounted on either side of the dam, then measure the target array on the dam. The computer would obtain the target position from storage, step the mount to that position and turn on an instrument to obtain the best signal return. This instrument, mounted with the distance meter, would consist of a laser and detector which would give azimuth and elevation corrections to the computer. The computer would then step the mount until the returning laser beam was centered in the detector thus correcting for the apparent change in target position due to atmospheric refraction. If no return beam is detected an error message would be generated, designating a particular target as non-operational.

With the mount pointed directly at the target and no error received, the computer can command the laser distance meter to take a measurement. The distance would then be stored in an array, the next target selected and the measurement process repeated.

When all the targets have been measured, possibly including a final look at the calibration targets to determine any drift in atmospheric refraction,




FUNCTIONAL FLOW DIAGRAM

Figure 3

corrections are applied. Data from weather instrumentation at the instrument site would be used to compute a rough refraction correction. The corrected data would then be compared with the actual distances from storage producing deflection values for each target. Any deflections greater than expected for normal movement of the dam would be flagged and a warning sent to the remote terminal. The rest of the data would be transmitted to the terminal for hard copy storage and/or stored at the computer site.

With this process complete, the computer would then calculate the time of the next measurement, power down the equipment and close the shelter waiting for the next start command.

## COMPONENT SPECIFICATION

After finalization of the configuration and functioning of the motion monitor, various components of the system were studied to determine the specifications necessary for each to meet the design requirements. Emphasis was placed on the ease with which they could be integrated into a monitoring system and on their present availability. The search for equipment was not meant to be exhaustive, only thorough enough to provide information on what products were available, what their specifications were and at what cost.

### Laser Distance Meter

The heart of the dam motion monitor is a laser ranging instrument. This type of equipment is becoming common place in applications where long distances must be accurately surveyed often over inhospitable terrain. It was not easy, however, to find an instrument meeting the combination of requirements needed in the performance of dam motion monitoring; namely a 3-kilometer range, better than 1 centimenter accuracy and ability to react to computer control.

The distance meters produced by Cubic Western Data, the Minitape HDM-70, and Tellurometer, the MA100, had range limitations of 1600 meters and 2000 meters, respectively, which made them unsuitable. Of the four instruments produced by Hewlett Packard, two, the HP3808-A and HP3820-A, combine sufficient range with automatic data collection capabilities. The 3808 proved better in

accuracy, $\pm$ (5mm + 1mm/km) as opposed to $\pm$ (5mm + 5mm/km), and required only a single 3-inch retroreflector to operate at 3 kilometers instead of 3 prisms for the 3820 at the same distance. Another instrument, the Terrameter LDM-2, was developed by Terra Technology to measure the movement of the earth along fault lines. The Terrameter measures distances using two frequencies of light to eliminate atmosphere caused errors and thus provide very high precision, 0.1 mm to 10 kilometers and 1:107 from 10 to 15 kilometers. It also operates under control of an internal mini computer which could be used to provide automatic measurement.

Of the two instruments capable of meeting the study requirements, the HP3808-A and the Terrameter, the latter had several undesirable features which lead to the selection of the Hewlett Packard instrument as a basis for distance meter specifications.

A first was a price which was higher by an order of magnitude due to the extreme accuracy and range capabilities built into the Terrameter. Second, due to the use of a polarization modulation measurement technique, it is necessary to use special parabolic target reflectors to preserve the polarization of the retuning laser beam. The third was the difficulty involved in modifying the built-in, non-motorized mount and computer to function with a dam monitoring system.

The specifications for a laser distance meter, for use in a dam motion monitoring system, based on an instrument comparable to the HP3808-A would be:

Range - 3 km minimum to a single retroreflecting prism
Accuracy - 1 part in 300000 minimum
Resolution - 1 mm or better
Measurement Rate - 5 minutes/reading maximum
Digital Output - external port providing control of measurement process and supplying digital data in either serial or parallel format
Power - operation from either 12 VDC or 110 VDC

Operating environment - 20°C to 55°C

0% to 100% humidity

Weight - 30 lbs maximum

Price - $10000

## Azimuth - Elevation Mount

Most of the instrument mounts presently available were designed to meet a specific need, i.e., the tracking of fast moving objects, gyro-stabilized air and ship-borne applications or pointing large or heavy payloads. A dam monitoring application does not require fast response, high angular rates, stabilization or high capacity. It does require long term reliability and reasonable resolution.

Modifying an existing design to lower its capacities proved expensive and, in most cases, unfeasible. Aeroflex Laboratories, Inc. quoted a price of $75,000 to modify one of their gyro-stabilized mounts.

The cheapest alternative available, approximatly $9000 for the mount and controller, was a line of motor driven modules made by Klinger Scientific Corp. for use in positioning components in optical laboratory set ups. A pair of these modules, one for azimuth and one for elevation, was capable of pointing the distance meter with the desired resolution but because of their development for laboratory use, their reliability in an uncontrolled environment was questionable.

The best alternative was a mount from Carson Astronomical Instruments, Inc. who specialize in designing mounts to meet custom tracking and positioning needs. One of their basic mounts, built to meet dam monitoring needs, would cost around $20000.

The specifications for a mount suitable for this dam monitoring application would be:

Type - two axis, elevation over azimuth preferred

Payload - 50 lb maximum

Activators - stepper motors on both axes

Zero position - mechanical stops required

Travel - ±15° elevation

±30° azimuth

Resolution - .3 to .5 arc minute

Angular velocity - .1° to 10° per sec

Controller inputs - CW and CCW step pulses for each axis

Controller outputs - on zero output for each axis

Power - 12 volt DC or 110 volt AC

Price - $20,000

Instrument Protection

In order to operate for long periods of time in remote locations, the instruments comprising the dam monitor will have to have some form of shelter as protection from vandalism as well as the environment. Most of the equipment, the computer in particular, will have a operating temperature range, generally somewhere between 0°and 100° F. This can be easily provided by a well-insolated enclosure, with special considerations made for heating and ventilation in particularly cold or hot climates. Such a shelter would also function to keep out rain and dust.

Since the distance meter will be enclosed, some form of opening must be made in the shelter through which measurements can be made. This could be a simple slit in the wall of the enclosure or a door with an activating mechanism controlled by the computer. The advantages of a door (better temperature control less dust and water vapor around the equipment and less chance for an occasional passerby to vandalize the monitor with rocks or sticks) offset the advantage of simplicity offered by a permanent opening.

Fiberglass and aluminum instrument domes are commercially available but motor activated doors are offered on only the large domes more suitable for manned instrumentation and observatories. Small domes in general are built to be portable and have hatches which are manually lifted off while the instrument is in use. These could be fitted with a motorized activator and control for automated use.

An alternative to a commercially available dome would be to build a shelter at the site. Since a foundation for the distance meter mount will have to be poured, the construction of a small cinder block or concrete structure would be relatively simple. All that would be necessary would be to incorporate a small roll up door similar to a garage door, and another door to access the equipment.

Targets

In order for the laser range meter to measure the distances to various points on the dam, an array of targets must be mounted on the dam to reflect the laser beam back to the instrument. Corner reflector prisms are ideal for this purpose because they are rigid and insensitive to alignment errors. Retroreflectors are specified by their aperature diameter and the angular deviation introduced between the entrant and exiting rays.

Some method of distinguishing between targets must be incorporated in their design because of the requirement that two targets may be mounted as close as 3 meters. Since the width of a 2-minute divergent beam is only 1.75 meters, only one target should be illuminated by the laser at a time; however, refraction caused errors in the apparent position of a target as viewed from the distance meter, could lead to confusion as to which of two closely spaced targets is being measured. One method would involve developing active mounts for the retroreflectors. Each mount would have a shutter mechanism and could be individually commanded to open and close, presenting only one reflector in the array to the laser beam. This negates the simple and passive nature of the corner reflector, however.

Since the entire dam will be viewed through essentially the same atmosphere, the refraction induced pointing errors should be approximately the same for all the targets. A relative position addressing scheme would take advantage of this to help pick up the correct target. Using this method, each target's position would be stored as relative movement from the previous target rather than absolute movement from the hardware zero position of the instrument mount. Once the distance meter is centered on the first calibration target,

most of the pointing error is accounted for and each relative move to the next target would point at its present apparent position, allowing the instrument to pick out the next target and not the apparent image of an adjacent reflector.

In a monitoring system designed to detect deflections of one centimeter, a distance offset of 10 to 20 centimeters of one reflector relative to an adjacent one would be immediately detectable if the instrument were measuring the wrong target. An error routine would then backtrack to the correct target and repeat the measurement. An actual deflection of the dam exactly matching the offset would be unlikely, but if it were to occur, the error routine would sense the fact that both targets were at the same distance and deduce the deflection.

This method, along with the use of relative positioning, would eliminate the necessity for active targets. Thus, a very simple mount can be used to hold the retroreflectors, consisting of a tube of sufficient length to protect the reflector from rain and dirt, a screw-on cap with the corner reflector mounted securely inside, and a base to anchor the mount onto the dam structure. Alignment of the target, because of the non-critical nature of the reflectors, could be as easy as sighting through the barrel of the mount and bending the base to point at the distance measuring instrument.

In locations where weather conditions warrant, the corner reflector must be protected against fogging and frost. The mounting will provide protection to a degree but since the surface of the reflector is in constant contact with the moist atmosphere around the dam, some form of anti-fog coating may be necessary. According to a U.S. Forest Service report, a coating of PAM, an anti-stick cooking spray, works adequately.

The specifications for the laser reflectors would be:

Type - glass corner reflector prisms
Aperature - 2.5 to 3 inches
Ray deviation - 5 arc seconds maximum
Price - $175 each in lots of 50

Target Centering

As a result of atmospheric refraction causing changes in the apparent position of a target when viewed from the distance meter, the stored target locations may not point the laser beam at the center of a target. Some way is needed to center the beam to obtain the best return signal for the distance measurement.

If signal strength readings are available form the distance meter, the computer could initiate a search routine, moving the laser beam around the stored target position until the maximum signal strength was found. In the case of the HP3808-A, signal strength readings are available but this mode of operation is not selectable from the input-output port and could not be used in an automated system without modification to the distance meter itself.

Where signal strength is not available, a device such as the one made by Carson Astronomical Instruments, Inc. could be used to center the beam. This instrument, developed to track a moving reflector, consists of a helium-neon laser whose beam is bounced off the reflector and received by a quadrant detector. This device would be mounted along with the laser distance meter. The output of the quad detector indicates the direction of the highest beam strength, i.e., up and to the left, and could be used by the computer to step the mount until all four sensors in the detector are receiving the same strength of signal. Then the distance meter would be turned on and commanded to measure the distance to the target.

The specifications for a beam centering device would be:

Type - Source: helium-neon laser
Receiver: quadrant detector
Control input - data enable
Control output - signals to indicate ±step in elevation and azimuth

## Control System

In order to replace the personnel required in dam motion monitoring, the equipment involved in the measurement process must be operated by an automatic controller. The functions of such a contol system have been outlined in the algorithm presented above. This system can be broken into four units: a digital computer, data storage, interfaces between the computer and other equipment and a remote console with a communication link.

### Computer

The computer unit of the control system performs two tasks. First, it acts as a programmable machine controller, giving commands to the various pieces of equipment and receiving their output data for storage. Its second function is to compute dam deflection values using the collected data. Both these tasks would be performed by a resident program following the algorithm detailed earlier.

Dealing with distance values of up to three kilometers with a resolution of a millimeter requires a binary word length of at least 21 bits. In realistic terms this would indicate the use of a computer with an internal data word of 32 bits or 16 bits if double precision arithmetic is used. Since computational speed is not necessary and the measurement task is fairly straightforward, a simple, single-board microprocessor, commonly used for machine control, could be applied to this task. The advantages of a higher order processor for developing a control system of this sort, however, offset its generally higher price.

The higher level languages such as BASIC and FORTRAN, which are available in more advanced computers, allow programming to be developed faster and with fewer difficulties than with the assembly and machine languages common to the simpler microprocessors. Program maintainence is also simplified by using a high level language and, in the case of dam monitoring, would allow the control system to be easily tailored to match the specific dam installation. As the monitoring process is improved over time, these changes could also be incorporated into existing systems with less effort.

Communication between mini and higher level computers and their peripheral devices is handled with plug-in modules. Special interfaces would have to be developed for a microprocessor based system. Data transfer to and from these peripherals is accommodated using simple read/write statements in the higher level language rather than having to write complicated device driver routines in assembly language.

Expansion of a minicomputer based system is simply a matter of plugging additional memory and device interface cards into the computer chassis. With a microprocessor based system this might involve a redesign of a part or the whole of the system.

As an example of the use of minicomputers for this task, two systems will be described at the end of this section. One will be based on Hewlett Packard's System 35 Desktop computer and the other on Digital Equipment Corp.'s PDP 11/4 minicomputer.

### Data Storage

Various types of information will have to be stored at the computer. These might include target positions, search patterns, past position corrections, actual distance measurements, present distances, deflection histories, refraction corrections and temperature and humidity histories.

Flexible disc storage is ideally suited to this function. Floppy disc drives are common in small systems where random access to data simplifies the storage and retrieval process. The drives and their controllers are also readily available from most computer manufacturers.

### Remote Terminal

In order to allow for measurement by command and to provide permanent hardcopy data and a warning in case of excessive dam movement, a terminal must be located in an office remote from the instrument. This capacity can be easily provided where telephone lines are accessible at the dam site by installing originate/answer modems at either end of a line connecting the dam monitor computer with the console keyboard/printer.

To give commands to the computer, an operator would dial the proper number. The call would be answered by the modem at the dam site and the line connected to the computer operating in its wait state. In the reverse mode, the computer, after finishing a measurement series, would contact the console using an automatic dialer and send the data to be printed for hardcopy storage. Warning information about system malfunction or dam movement could also be sent, all without office personnel present if measurements are taken after hours.

## Interfaces

Communication between the computer and various peripheral devices is facilitated by interfaces. Data sent to and from the disc unit passes through a controller which places the data in the right format. Information on temperature and humidity is input to an analog to digital interface before it is read by the computer. The computer sends digital pulses over the correct lines to the mount to obtain step motion from the drive motors.

These interfaces are available in the form of plug-in boards for both the HP and DEC computers. In the case of Hewlett Packard, their 6940-B Multiprogrammer connects directly to their computers and can be fitted with cards for temperature collection, analog to digital conversion, relay control and even stepper motor control. Digital and analog cards perform the same functions in the PDP 11/04 from DEC. Communication to the disc drives and modems in both systems is through standard RS232 interfaces.

Connection to the HP3808-A distance meter is provided through a modification to a standard HP interface board developed by their Civil Engineering Division. For the DEC system an interface would have to be developed from their universal interface board.

## Specifications

Since the dam monitor's ability to function depends on the control system to intercorrect devices not meant to work together, the specifications for control are, in large, determined by the other equipment selected for the dam monitoring

system. In particular, the number and mix of digital input and output lines and analog controls and inputs, depend on the type of equipment used to actuate the shelter door, weather instrumentation used, power supply, etc.

Thus, the specifications and example systems given below are not necessarily exact but mainly for the purpose of illustrating what might be necessary.

Computer:

| | |
|---|---|
| Word length | 16 binary bits minimum |
| Language | BASIC with assembly language capability |
| Memory | 8K to 16K minimum |

Data Storage:

| | |
|---|---|
| Type | Flexible Disc |
| Capacity | 256K to 500K bytes per disc |

Remote Terminal:

| | |
|---|---|
| Type | Hard copy printer with keyboard |
| Interface | RS-232 Serial port |
| | 2 answer/originate modems |
| | automatic dialer |

Interfaces:

RS-232 interface to terminal and flexible disc drive if needed
10 digital input lines minimum
10 digital output lines minimum
3 analog input lines minimum
1 serial input port to HP3808 180KHz; 56 bits serial input data.

A Hewlett Packard control system would consist of the following equipment:

| PART | DESCRIPTION | QTY | COST |
|---|---|---|---|
| 9835B | Desk top computer | 1 | 8700. |
| 98331 | Mass storage ROM | 1 | 500. |
| 98332 | General I/O ROM | 1 | 750. |
| 98035A | Real time clock | 1 | 600. |
| 9878A | I/O Expander | 1 | 1200. |
| 9885M | Flexible Disc Drive | 1 | 3750. |
| 98032A | 16-bit Parallel I/O Interface | 1 | 520. |
| 98036A | RS-232-C Interface | 1 | 600. |
| 6940B | Multiprogrammer | 1 | 1700. |
| 69335A | Stepper Motor Control | 2 | 800. |
| 69351B | Voltage Regulator | 1 | 150. |
| 69421B | Voltage Monitor | 3 | 1500. |
| 69331A | Digital Output | 1 | 210. |
| 69431A | Digital Input | 1 | 210. |
| 69330A | Relay Output | 1 | 300. |
| 2635A | Printing Terminal | 1 | 3450. |
| | | TOTAL | 24,940. |

A system based on the Digital Equipment Corporation PDP 11/04 would consist of the following:

| PART | DESCRIPTION | QTY | COST |
|---|---|---|---|
| PDP11/04 | Computer | 1 | 8770. |
| DR11-M | Digital Output | 1 | 380. |
| ARKT-11 | Analog Input | 1 | 2080. |
| DL11-E | RS-232-C Interface | 2 | 1540. |
| RXZ11-BA | Floppy Disc Drive | 1 | 3990. |
| HP613-AA | Equipment Cabinet | 1 | 985. |
| DD11-CK | Expansion Box and Power Supply | 1 | 400. |
| M1710 | Universal Interface | 1 | 275. |
| QJ642-A4 | RSX-11/5 Operating System | 1 | 1650. |
| | Basic Compiler | 1 | 880. |
| DL11-WB | Console with Modem | 1 | 770. |
| LA36 | Printer | 1 | 1950. |
| | | TOTAL | 23,670. |

Power Supplies

Supplying power to the dam monitor is a simple task when 110 VAC electricity is available. Most of the instruments and equipment will plug into common household sockets. Other equipment such as the HP3808 can use commercially available converters supplying direct current at the appropriate voltage.

The most critical times for monitoring dam movement, however, will occur when the power lines may be down such as during periods of flood and following earthquakes. For this reason, a more complicated storage system might be necessary to allow operation in the face of a power outage.

Two methods of supplying emergency power could be used. The first entails switching to a backup system when a power failure is detected. This backup system would consist of a bank of batteries, capable of running the system for a period of time, along with the necessary equipment to convert the stored electricity to a form needed by the monitoring equipment.

The second method would eliminate the possibilities of the backup system not switching properly or not being sufficiently charged. By placing the batteries and conversion equipment in line with the main power to the monitor system, they would be in constant service supplying the monitoring equipment and would be continually charged from the external power lines. Thus, when external power failed, the fully charged batteries would supply power until the power lines were restored.

## Conclusions

In the selection of the method and instrumentation for the detection and monitoring of dam movement, this study has touched on many technologies and fields of investigation. These include laser ranging, surveying, optics, meteorology, computer automation, digital and analog interfacing, civil and dam engineering and dam safety. Any advances in these rapidly changing areas would affect the development of dam motion monitoring.

Availability has played a large part in the development of the system presented here. In particular, the expanding use of highly accurate laser distance meters in surveying applications and the ease with which many computers can be configured and programmed to control a large range of devices have lead to the development of a fairly simple, accurate instrument system based on off-the-shelf technology.

This dam monitor consists of a laser distance meter pointed at an array of reflecting targets mounted on the dam structure. Individual targets are picked out by an azimuth-elevation mount carrying the laser and controlled by a minicomputer. The computer also commands the measurement process and auxiliary equipment through the appropriate interfaces. Dam deflection data are compiled by the computer and sent to a remote sight manned by the dam operators. On-site data storage is available in the form of flexible discs. Excessive movement of the dam or any indications of equipment failure would cause a warning to be displayed on the operators console and allow the appropriate actions to be taken.

At this point, this design seems to be feasible and its application to dam monitoring involves no great difficulty. Its theoretical accuracy is great enough to suit the requirements for measuring dam motion and its cost is not large compared to the potential savings in property and life if a dam failure is prevented. The construction of a prototype should be possible using the specifications given in this report and its testing in an actual monitoring environment should prove its worth as a dam motion monitor.

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## APPENDIX

### Atmospheric Refraction Model

In this study, a ray-trace model was used to obtain the most accurate value possible for a given set of atmospheric conditions. The model allows consideration of the effects of local variations in atmospheric conditions, primarily temperature and relative humidity. It assumes a planar reference surface with atmospheric layers stratified with respect to it. These layers are grouped into segments such that each segment is defined by characteristics of the medium over which the ray is passing. It also allows acknowledgment of the differing atmospheric temperature and relative humidity as its water vapor content varies.

The refraction corrections are computed within each individual segment, and at the interface between each adjacent pair of segments. These corrections are then summed to obtain a value for the total refraction effect along the entire path. Two APL functions were written for this purpose: LAYER, which computes the refraction correction within each segment, and INTER, which computes the corrected angle of incidence between two adjacent segments and the base input values for the new segment. LAYER and INTER are applied in succession to a given ray, from the selected station to the selected endpoint. This results in a model which is easily modified at numerous points along the ray's path to respond to changing atmospheric conditions.

The segmentation approach was chosen because of the presence of significant variations in atmospheric conditions between air over land and air over water. With this method, the corrections over a constant region (land or water) may be calculated and the interface between the two handled separately. The model may, therefore, be applied to any topography, rather than being restricted to a depiction of any specific locale.

### LAYER

The function LAYER is a planar atmospheric model which assumes a series of flat layers parallel to a plane selected to approximate the surface of the earth.

Each of these layers is defined according to its distance from the surface. The initial distance, distance increment, and final distance are all unrestricted input values. At each boundary between layers, the atmospheric conditions are redefined according to two distance dependent lapse rates: the adiabatic temperature lapse rate and the relative humidity lapse rate. From these two revised parameters, a new index of refraction is computed and the corrections for the apparent angle and distance are computed for the new level. LAYER is applied to each segment in this manner. Its purpose is to determine the internal refraction corrections for that set of atmospheric conditions to any degree of accuracy specified; that is, with as many internal layers as requested.

To provide the necessary versatility, LAYER has been designed to require many input values: a total of 13. This makes the function highly responsive to the various atmospheric properties which define conditions within a segment. The required input consists of the medium over which the ray is passing, the estimated position of the end of the segment, the distance increment value, the value of the entrance angle at the start of the segment, the station position, temperature, and relative humidity at the start of the segment, the humidity and temperature lapse rates, the initial and final incremental values for the temperature lapse rate multiple, and (optionally) the refractive modulus at the start of the segment.

## INTER

INTER is designed as an interface between segments. Where LAYER computes the internal refraction corrections based on the systematic relationships among a given set of input variables, INTER computes the refraction correction at the interface point between segments where those variables are discontinuous. The corrected conditions calculated in LAYER for the end of one segment are not equal to the base conditions for the next segment; there will be a certain amount of change in values of parameters between the two segments because of the different nature of the two segments. INTER, therefore, allows the meshing together of two segments of widely differing input values.

The principal purpose of the segment model is to arrange a sequential group of segments, calculate the corrected ray as it leaves each segment, compute the conditions at the interface, and use the corrected ray and computed atmospheric conditions as the base conditions for the entrance of the ray into the subsequent segment, summing the corrections until the end of the final segment is reached.

The most obvious parametric change from an air mass over land to one over water is in the relative humidity. From lack of accurate information to the contrary, the air over water is assumed to be completely saturated; that is, the relative humidity is equal to 100% over the entire segment. The air over land, however, is assumed to be unsaturated and can have any value of relative humidity as supplied on input. Any number of land-based segments may be used to depict the varying conditions of humidity that may occur in an area.

INTER requires as input the temperature, relative humidity, pressure and corrected exit angle at the end of the first segment and the relative humidity at the start of the second segment. From these values, the corrected exit angle, refractive modulus, and temperature of the start of the second segment are all computed. These are entered as input for the next LAYER run of the new segment. Thus in LAYER, the temperature and relative humidity are incremented according to distance from the reference surface, changing all of the other parameters. In INTER, only the relative humidity is changed, which results in a temperature change and alteration of all of the other parameters to be entered in the next LAYER run.

This sequence is repeated until the desired target point is reached.

There are four lapse rates used in the model: the distance lapse rate, the relative humidity lapse rate, the adiabatic temperature lapse rate, and the gradient coefficient for the temperature lapse rate.

The distance lapse rate is completely arbitrary, used solely as a user-defined basis for determination of the internal layers within each segment as is required by the model. The distance may begin and end incrementing at any

given points. The increment value may be either positive or negative, as it is simply added to the previous value inside an iterative loop.

No standard relative humidity lapse rate was available to accurately describe the over-land, over-water situation found near a dam. For this reason, almost all of the factors associated with humidity in the model were assigned assumed values. This part of the model is very flexible, however, and may easily be adopted to any more accurate humidity lapse rate that might be found.

One of the major assumptions concerns saturation rates. The air mass over water is treated as completely saturated for the altitudes involved in this study. At higher altitudes, it is recognized that the relative humidity would be less than 100%. Furthermore, it is assumed that the air in contact with the land remains unsaturated. These differences in relative humidity are handled by INTER.

The humidity lapse rate serves as a gradient, and must be chosen to approximate actual conditions. It cannot be exact because the humidity may rise and fall several times over a segment of land or water, as a result of either seasonal or diurnal variations in factors such as light and shadow patterns and wind conditions.

The temperature lapse rate is one of the most important parameters in the model. It effects every atmospheric parameter related to the calculation of the refraction corrections except the relative humidity. Because the actual value also varies with relative humidity, an accurate gradient could not be defined which would apply to all conditions. Instead, a value was taken from the standard atmosphere tables. The adiabatic lapse rate was chosen, defined as approximately 0.01 degrees Celsius per meter in the range of this model. It is easily manipulated by the use of multiples, and the conversion between the lapse rate for saturated and that for unsaturated air is easily achieved.

Adiabatic implies no loss of heat; the volume of gas is assumed to undergo changes in state (heating/cooling) while thermally insulated from its environment. This allows linkage of change in temperature to change in altitude, which occurs even in the absence of other environmental factors which the model treats separately.

For unsaturated conditions, it is assumed that the adiabatic lapse rate for dry air is in effect. Once saturation is achieved, it is converted to the saturated adiabatic lapse rate by application of an approximate multiple. At 30 degrees Celsius, the saturated adiabatic lapse rate is equal to one-third of the dry adiabatic lapse rate; at zero degrees it is equal to two-thirds of the dry rate, and at -30 degrees to 95% of it.

Temperature is redefined at each new level within a segment solely in terms of the change in distance from the reference surface, and all other parameters are redefined from temperature. Each layer within a segment is thus completely defined with respect to the base values in terms of this distance.

From 500 to 3000 feet MSL, which encompasses this model, the temperature gradient ranges from approximately -1.5 to 0.5 times the dry adiabatic lapse rate. Because of this variance, there exists an option to run the LAYER corrections for a segment using the same conditions throughout except for different dry adiabatic lapse rate coefficients.

The purpose of this lapse rate is to compensate to some degree for the assumptions implicit in use of the dry adiabatic lapse rate. The optional gradient coefficient is totally under the user's control and may be applied as the situation requires.

Normal conditions are indicated by a negative coefficient, while a positive one is characteristic of the existence of an inversion layer. There is no limit on the type which may be used. For example, the effect of no change in coefficient may be obtained by using a value of -1 for the initial multiple, -0.9 for the final one, and 0.2 for the increment. This will result in one run of LAYER at the normal adiabatic lapse rate entered as input.

```
      ∇INTER[⎕]∇
    ∇ INTER A;T;NZN;ZNRD;P;T;N;NO;NI;DELTA;COREL
[1]   →((ρA)≠7)/ERR
[2]  ⍝ INPUT: TEMP COMING FROM, RH AT STA, TEMP AT STA, NEW RH, COREL, BASE TEMP FOR FIRST SEG., PRESSURE AT STA.
[3]   T←A[3]+273 ⋄ NZN←90-A[5] ⋄ ZNRD←NZN÷57.29578
[4]   PSTA←A[7]
[5]   PW←(A[2]×0.0611)×10*((7.5×A[3])÷(237.3+A[3]))
[6]   PS←PW÷A[2] ⋄ P←1013.25×(288.15÷(A[1]+273))*-5.255876
[7]   VT←T÷(1-0.37803×(PW÷A[7])) ⋄ N←(77.6×P÷(A[1]+273))-0.06×PW
[8]   NO←1+N×1E¯6
[9]   '
          RH          T          TO          PW          P          N
      '
[10]  '6F10.4' ⎕FMT(A[2];A[1];A[3];PW;P;N)
[11]  PW←A[4]×PS ⋄ T←VT×(1-0.37803×(PW÷A[7]))
[12]  PW←(A[4]×0.0611)×10*((7.5×(T-273))÷(237.3+(T-273)))
[13]  P←1013.25×(288.15÷T)*-5.255876
[14]  N←(77.6×P÷T)-0.06×PW ⋄ NI←1+N×1E¯6
[15]  T←T-273
[16]  '6F10.4' ⎕FMT(A[4];T;A[3];PW;P;N)
[17]  ZNRD←¯1○((NO÷NI)×(1○ZNRD)) ⋄ NZN←ZNRD×57.29578
[18]  DELTA←A[5]-90-NZN ⋄ COREL←90-NZN
[19]  '
            COREL                    DELTA                NO               NI          NEW T      NEW P
      '
[20]  '2F20.15,2F15.10,2F10.4' ⎕FMT(COREL;DELTA;NO;NI;T;P)
[21]  →0
[22] ERR:'INCORRECT NUMBER OF INPUT VALUES: ';(ρA);' WERE ENTERED INSTEAD OF 7.'
    ∇
```

```
    ∇LAYER[⎕]∇
  ∇ LAYER A;NO;ZG;ELEV;SR;XG;NZN;COREL;NI;NN;FLAT;N;T;P;F;MUPL;MUPLE;PW;TC;IF;DELTA;LIMIT;VST;HST;VDIF;HDIF;TDIF
[1]   →((ρA)≠13)/ERR
[2]   ⍝ THE INPUT VALUES REPRESENT, IN ORDER: 1=OVER LAND, 2=OVER WATER, EST. ALT., ALT DECREMENT, OBS EL, STA, BASE
[3]   ⍝ TEMP IN DEGREES C, RH AT STATION IN PERCENT, RHL IN PERCENT PER FOOT, DRY ADIABATIC LAPSE RATE IN C PER METER, INITIAL
[4]   ⍝ DALR MULTIPLE, FINAL DALR MULTIPLE, DALR MULTIPLE INCREMENT, CORRECTED REFRACTIVE MODULUS. (13 VALUES)
[5]   MUPL←A[10]
[6]  ENTER:ZG←A[5] ⍝ ELEV←A[4] ⍝ LIMIT←0 ⍝ COREL←ELEV ⍝ ALR←A[9] ⍝ NZN←90-ELEV
[7]   →(A[4]≤90)/ACUTE ⍝ A[4]←|(180-A[4])
[8]  ACUTE:VST←A[2] ⍝ HST←(A[2]÷1○(A[4]÷57.29578))×2○(A[4]÷57.29578)
[9]   →(A[13]=0)/NLP ⍝ N←A[13] ⍝ TC←A[6] ⍝ →PRINT
[10] NLP:TC←A[6]+(A[5]÷3.28)×A[9]×MUPL ⍝ T←TC+273 ⍝ PW←(0.0611×A[7])×10*((7.5×TC)÷(237.3+TC))
[11]  P←1013.25×(288.15÷T)*-5.255876 ⍝ N←(77.6×P÷T)-0.06×PW
[12] PRINT:
[13] '
            ZG          XG            NI                NO              TOTAL REFR          TI          PWI      PI          CORR EL
     '
[14] LOOP:NO←1+N×1E¯6 ⍝ ZNRD←NZN÷57.29578
[15]  ZG←ZG+A[3] ⍝ →(((ZG>A[2])∧A[2]>A[5])∨((ZG<A[2])∧A[2]<A[5])∨N≤LIMIT)/EXIT ⍝ XG←ZG×3○ZNRD
[16]  F←((|(ZG-A[5]))×A[8])+A[7] ⍝ PW←((0.0611×F)×10*((7.5×TC)÷(237.3+TC))) ⍝ →(F>0)/BRANCH ⍝ F←A[7]
[17] BRANCH:→((F<100)∨A[illegible]≠1)/COMP ⍝ ALR←A[9]÷3 ⍝ MUPL←¯1 ⍝ F←100
[18] COMP:TC←A[6]+((ZG-A[5])÷3.28)×ALR×MUPL ⍝ T←TC+273
[19]  P←1013.25×(288.15÷T)*-5.255876 ⍝ N←(77.6×P÷T)-0.06×PW
[20]  NI←1+N÷1000000
[21]  ZNRD←¯1○((NO÷NI)×(1○ZNRD)) ⍝ NZN←ZNRD×57.29578
[22]  DELTA←COREL-90-NZN ⍝ COREL←90-NZN ⍝ FLAT←ELEV-COREL
[23]  '2F10.4,2F15.10,F20.15,3F10.4,F20.15' ⎕FMT(ZG;XG;NI;NO;FLAT;T;PW;P;COREL)
[24]  →LOOP
[25] EXIT:'


              CORRECTED ENDPOINT (IN FEET) AND CORRECTED ATM. PARAMETERS AT END OF RAY
          ZG          XG            CORR EL            TEMP       REL HUMID   V DISP     H DISP     R DISP
     '
[26]  T←T-273
[27]  CORELA←COREL
[28]  →(COREL≤90)/ACT ⍝ CORELA←|(180-COREL)
[29] ACT:SR←((A[2]*2)+XG*2)*0.5 ⍝ VDIF←(SR×1○(CORELA÷57.29578))-VST ⍝ HDIF←(SR×2○(CORELA÷57.29578))-HST
[30]  TDIF←((VDIF*2)+HDIF*2)*0.5 ⍝ CORELA←COREL
[31]  '2F10.4,F20.15,5F10.4' ⎕FMT(A[2];XG;COREL;T;F;VDIF;HDIF;TDIF)
[32]  MUPLE←MUPL+A[12] ⍝ →((A[9]=0)∨(MUPLE>A[11])∨ALR=A[9]÷3)/0
[33]  '


                                        DRY ADIABATIC LAPSE RATE MULTIPLE NOW EQUALS: ';MUPLE
[34]  MUPL←MUPLE ⍝ →ENTER
[35] ERR:'INCORRECT NUMBER OF INPUT VALUES: ';(ρA);' WERE ENTERED INSTEAD OF 13.'
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Manufacturers

ABA Electomechanical Systems - instrument mounts
P.O. Box 500
Pinellas Park, FL 33565
(813) 541-6681

Aeroflex Laboratories, Inc. - instrument mounts
South Service Road
Plainview, NY 11803
(516) 694-6700

Carson Astronomical Instruments, Inc. - instrument mounts, target centering
120 Erbe, NE
Albuquerque, NM 87123
(505) 294-5067

Cubic Western - laser distance meter
5650 Kearny Mesa Road
San Diego, CA 92111
(714) 268-3100

Digital Equipment Corp. - computers
146 Main Street
Maynard, MA 01754
(617) 481-9511

Hewlett Packard Civil Engineering Division - laser distance meter
P.O. Box 301
Loveland, CO 80537
(303) 667-5000

Hewlett Packard Desktop Computer Division - computers
3400 East Harmony Road
Fort Collins, CO 80525
(303) 226-3800

Klinger Scientific Corp. - instrument mounts
83-45 Parsons Boulevard
Jamaica, NY 11432
(212) 657-0335

Parabam, Inc. - instrument shelters
3017 East Las Hemanas Street
Compton, CA 90221
(213) 537-1771

Photo Sonics - instrument mounts
820 South Maraposa Street
Burbank, CA 91506
(213) 849-6251

Tellurometer - laser distance meter
89 Marcus Boulevard
Hauppauge, NY 11787
(516) 231-7710

Terra Metrics - laser collimator
16027 West Fifth Avenue
Golden, CO 80401
(303) 279-7813

Terra Technology Corp. - laser distance meter
3860 - 148th Avenue, NE
Redmond, WA 98052
(206) 883-7300

Towill Surveying - laser interferometry
San Francisco, CA
(415) 982-1758

Zygo Corp. - retroreflectors
1088 Newfield Street
Middletown, CT 06457
(203) 347-8506